Invited Paper

Open questions in site characterization and turbulence parameter measurements

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ABSTRACT

With the development of increasingly larger and more complex telescopes and instrumentation, site testing and characterization efforts also increase in both magnitude and complexity. This happens because the investment into larger observatories is higher and because new technologies, such as adaptive optics, require knowledge about parameters that did not matter previously, such as the vertical distribution of turbulence. We present examples of remaining questions which, to date, are not generally addressed by "standard" site characterization efforts, either because they are technically not (yet) feasible or because they are impractical. We center our observations around the experience gained during the Thirty Meter Telescope (TMT) site testing effort with an emphasis on turbulence measurements, but our findings are applicable in general to other current and future projects as well.

Keywords: Site testing, extremely large telescopes, Thirty Meter Telescope

1. INTRODUCTION

In 1909, a site testing expedition to Copiapó in Northern Chile was concerned with two of the same site characteristics that are still at the heart of modern site testing projects for optical/infrared astronomical observatories, namely cloud cover and seeing.[1] However, seeing was not measured, was addressed in a qualitative way only and was pointed out as an open question that should be resolved by a follow-up expedition. 100 years later, site testing projects are still addressing the same basic question of finding the site most suitable for the given observatory, but are using increasingly more complex instrument suites which can measure a larger set of parameters and/or achieve higher accuracy or longer baselines in the measurement of a given parameter.

The increase in magnitude and complexity happens not only because the investment into increasingly larger observatories is higher and therefore warrants a more extensive site characterization effort, but also because parameters that did not use to matter previously become important. An example of such a parameter is the vertical distribution of turbulence, which has no effect on seeing-limited observations (only the integrated seeing matters in this case), but matters for single-conjugate adaptive optics (AO) systems, and becomes even more important for multi-conjugate adaptive optics systems.

Nevertheless, no matter how extensive the site testing project is, there will always remain questions that have not been addressed, either because the required instrumentation did not exist at the time or because it was not feasible for practical reasons to operate it during the project. In this paper, we use the Thirty Meter Telescope (TMT) project and its site testing work as a recent example of open questions remaining after an extensive multi-year site testing campaign.

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Adaptive Optics Systems II, edited by Brent L. Ellerbroek, Michael Hart, Norbert Hubin, Peter L. Wizinowich,
Proc. of SPIE Vol. 7736, 77361Z · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857412

Table 1. List of TMT candidate sites selected for on-site testing.

Site Name	Elevation	Latitude [deg N]	Longitude [deg W]	Characteristics
Cerro Tolar	2290 m	-21.9639	70.0997	Northern Chile, coastal site
Cerro Armazones	3064 m	-24.5893	70.1917	Northern Chile, coastal site
Cerro Tolonchar	4480 m	-23.9361	67.9766	Northern Chile, inland site
San Pedro Mártir	2830 m	31.0456	115.4691	Baja California, Mexico; ∼60 km from ocean
Mauna Kea 13N	4050 m	19.8330	155.4810	Big Island, Hawai'i; island site

2. SUMMARY OF TMT SITE TESTING

We put the open questions of the TMT site testing work into context by beginning with a brief description of the project and the questions that were addressed. Detailed accounts of the TMT candidate sites, instruments, parameters and results are given elsewhere. We point in particular to the 12-paper series of TMT Site Testing results,[2] hereafter referred to as TST for the series and TST-1 to TST-12 for the individual papers; and to the final site testing report and results reports, which are available on the TMT Site Testing Public Database Server.[3]

In 2003, on-site testing began on the first two of the five sites which had been selected as candidate sites, Cerros Tolar, Armazones and Tolonchar in northern Chile, San Pedro Mártir on northern Baja California, Mexico, and the 13 North location on Mauna Kea, Hawaii. Test equipment was installed on the other three sites by 2005, with additions of new instruments continuing throughout the site testing period on all sites. All data taken until the end of February 2008 were presented in the final site testing report issued in April 2008, after which the instruments suites were decommissioned one by one. See Table 1 for a list of the sites and their coordinates and Table 2 for the instrument deployment dates. The TMT board of directors selected Mauna Kea as the preferred site for the Thirty Meter Telescope in July 2009.[4]

Table 2. Dates of first data acquisitions of the different instruments for each candidate site. Note that we only had three sets of SODARs and three IRMAs, which were rotated among the sites. Also note that the 30 m tower on San Pedro Mártir was set up and operated by the LSST project from December 2005 to May 2006.

	Tolar	Armazones	Tolonchar	San Pedro Mártir	Mauna Kea 13N
Weather station	Apr 03	Jul 03	Nov 05	Oct 04	Jun 05
DIMM	Oct 03	Nov 04	Nov 05	Oct 04	Jun 05
MASS	Jan 04	Nov 04	Jan 06	Oct 04	Jul 05
SODAR	—	Mar 05	Feb 06	Mar 06	Oct 05
All-sky camera	Oct 05	Oct 05	Nov 05	Jul 05	Jun 06
Sonic anemom.	Feb 06	Feb 06	Mar 06	May 06	Nov 05
Dust sensor	Feb 06	Feb 06	Mar 06	May 06	Nov 05
30 m tower	—	Sep 06	Mar 07	Dec 05	—
IRMA	—	Jan 07	Mar 07	—	Feb 07

Technical site properties were assessed predominantly through data acquired in a multi-year study of the site conditions using identical equipment. To acquire these data, the TMT site testing team operated remote site monitoring stations at each of the candidate sites. These stations included the following instrumentation:

Differential Image Motion Monitor (DIMM):

Differential image motion monitors (DIMMs) are currently the standard for measuring the integrated atmospheric seeing using small-aperture telescopes.[5] At the candidate sites, the telescopes were installed on 6.5 m towers. We use our DIMMs to measure the seeing, its temporal variability and to verify isoplanatic angle, turbulence coherence time, cloud cover and atmospheric transparency results taken with other instruments.

Multi-Aperture Scintillation Sensor (MASS):

Integrated in the same physical instrument as the DIMM is a Multi-Aperture Scintillation Sensor (MASS). A MASS produces six-layer measurements of the turbulence profile, excluding the first few hundreds of meters.[6] The layers are centered around 0.5, 1, 2, 4, 8 and 16 km elevation. The ground layer turbulence strength can then be calculated from the difference between the DIMM and MASS seeing. In addition to turbulence profiles, we also measure the isoplanatic angle, atmospheric coherence time and temporal variability of the MASS seeing. Atmospheric transparency measurements are also taken and cloud cover measurement from the all-sky cameras (described below) are verified.

Sound Detection and Ranging (SODAR) acoustic sounder:

SODAR (SOund Detection And Ranging) is the acoustic equivalent of RADAR. SODAR instruments have the capability of measuring both turbulence and wind velocity profiles in the atmospheric ground layer with high resolution. In order to study the lower part of the atmosphere, below the range of the MASS, we use a pair of SODARs that complement each other to sample elevations from 10 – 800 m.

Automatic Weather Station (AWS):

Commercial automatic weather stations (AWSs) were deployed at all sites to measure air temperature, wind speed and direction, relative humidity, barometric pressure, solar irradiance and the occurrence of precipitation. The AWS sensors were installed between 1.5 and 2.5 m above the ground. Soil temperature, net radiation above the ground and ground heat flux sensors were used at some sites, but were not part of all site setups.

At each site, a sonic anemometer was placed 7 m above the ground. It measured wind speed and direction and a "sonic temperature" (proportional to temperature, but also dependent on humidity and other parameters). The raw data for turbulence measurements were also taken and saved.

We also installed 30 m towers on Armazones and Tolonchar. These were equipped with sonic anemometers and air temperature sensors at the 11, 20 and 30 (or 28) m levels. A 30 m tower was also set up and operated by the Large Synoptic Survey Telescope (LSST) project at San Pedro Mártir. The data are available to TMT through a data-sharing agreement involving all instruments either project has deployed at San Pedro Mártir.

All-sky camera (ASCA):

All-sky cameras (ASCAs) were deployed at all candidate sites, with the ASCA at San Pedro Mártir being owned by LSST. A detailed description of the cameras is given in Ref. 7. We use the ASCAs mainly to measure cloud cover and light pollution at the candidate sites. The usable observing time fraction of the sites is also assessed based on these measurements.

Infrared Radiometer for Millimetre Astronomy (IRMA):

Three Infrared Radiometer for Millimetre Astronomy (IRMA) units from the University of Lethbridge measured the sky flux around 20 μm ($\sim$16.5 – 21.5 μm) wavelength. The precipitable water vapor (PWV) value can be calculated from this flux by use of a suitable atmospheric model.[8] The three units were deployed on Armazones, Tolonchar and Mauna Kea 13N. PWV was also analyzed through the use of the weather station data, radiosondes launched at nearby airports, and radiometers operated by other groups at or close to the TMT candidate sites.

Dust Sensor:

Commercial dust sensors were mounted at the 7-m level and measured the particle count in five different channels, for particle sizes 0.3, 0.5, 1.0, 2.0 and 5.0 μm. Here, the given size is a lower limit, each channel counts all particles with sizes equal to or larger than the respective value.

The TMT instrument suites were robotic and autonomous systems that did not require any operators or user interventions for standard operation. Nevertheless, they were constantly connected via the Internet, enabling full manual control and a wide variety of remote trouble-shooting. Data were available in real time via a website and were automatically loaded into a central database each morning.

The original goal of the TMT site selection campaign was to take on-site measurements of all major parameters (e.g. weather, seeing) for at least 2 years, and for at least one year for all other parameters. This was achieved or exceeded for most instruments, but was not possible in all cases for practical reasons. Dates of the first deployments of all instruments are shown in Table 2. Note that we do not have five sets of all instruments, so that not all of them have been installed continuously at each site since the dates given in the table.

In addition to the on-site testing, the sites were also characterized through the use of computational fluid dynamics (CFD) simulations and the analysis of satellite images. CFD simulation were used to study the wind, temperature and turbulence behavior at the site. They are also used extensively in the analysis of other aspects of TMT, such as dome and mirror seeing and wind buffeting, as is reported elsewhere at this conference.[9, 10] Several satellite studies of cloud cover and PWV at the TMT candidate sites were done both before and during the on-site testing period (see, for example, Ref. 11). The results of the earlier studies were used for the pre-selection of candidate sites. The main purpose of the later studies was to provide results that are simultaneous with the data taken at the sites.

As a final note we point out that the calibration of the results and the comparability of the results from site to site, while critical, are not discussed here. It is, of course, important to recognize that a reliable comparison of data sets is only possible if great care is taken to calibrate all instruments, stringent setup and operation procedures are adhered to and analysis criteria are applied in equivalent ways. The calibration of the instruments therefore accounted for a large part of the work done by the TMT site testing team and is a common thread through all TST papers. Even so, the uncertainties of measurements, especially when compared from site to site, is sometimes difficult to assess since no absolute reference exists for most parameters. It is, however, not a fundamental open issue and is therefore not treated in this paper.

For the same reason, we also do not address parameters for which insufficient amounts of data exist at one or all sites due to, for example, technical problems with the equipment or an insufficient number of instruments to equip all sites, as the solution to these problems is obvious. Also note that this paper is not meant as a comprehensive review of open site characterization questions for all applications and parameters, but rather as a case study of the TMT site testing project with examples of additions and improvements that could be made to future site testing or characterization efforts for similar projects.

The remaining sections describe the open questions that were not or could not be addressed during the TMT site testing work, as well as methods and instruments that can be used to address these issues.

3. TEMPORAL CHARACTERISTICS OF THE DATA

Every site testing and characterization effort is limited by the practical constraints imposed on it, including in particular the temporal characteristics of the measurements. On long time scales, this presents the question whether the data taken during the limited time when testing took place are representative for the long-term conditions of the site. Problems caused by gaps in the data due to equipment failures, weather or other scheduled or unscheduled breaks also pose problems for the interpretation of the results. It is also generally unclear if and how climate change will affect the atmospheric properties of a site. On shorter time scales, some properties of the measured parameters might not be accessible due to the data acquisition characteristics such as integration times and duty cycles of the equipment.

3.1. Representativeness of the Data

One of the guiding principles of the TMT site testing effort was that at least one full annual cycle of data was needed for each parameter and candidate site, with a goal of at least two years of data. We were in the lucky position to be able to start the site testing work early in the project and to test sites for a period of approximately five years overall. As a result, equipment was installed at each site for at least 2.5 years, and some instruments were installed at two of the sites (Cerros Tolar and Armazones) for more than 4 years. We thus achieved our goal of at least 2 annual cycles for most instruments at most sites. Nevertheless, practical considerations also resulted in some instruments operating for shorter amounts of time at some sites and even not being installed at all at a given site in a few cases. Details about the deployment schedules and the amount of data available from each instrument beyond what is shown in Table 2 are given in the papers of the TST series.

Even with such a comparatively extensive data set, the representativeness of a given parameter is not necessarily straight forward to address. If a multi-year record of atmospheric conditions exists for a site, a first step can be taken by inspecting the behavior of the parameter throughout this period. For the TMT candidate sites we observed that most have stable or repeating patterns throughout the years. It is therefore likely that these are representative for the longer-term conditions at the site. However, we also observe months and seasons that show signicantly different conditions from one year to the next for certain parameters at some sites. For example, conditions during the southern hemisphere winter of 2007 were noticeable "harsher" (cloudier, windier, stronger turbulence) at Armazones than during the other years. With only two to four years of data available, depending on the parameter in question, it is not always possible in a case like this to decide which of these periods are typical, or more typical, for long-term conditions and how frequently such apparently exceptional conditions occur.

More than that, some regional and global atmospheric conditions change on the scale of a few years and longer as a result of the phase of atmospheric oscillations, such as El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and its interactions (for instance, see Ref. 12). Thus, even a two or three year testing period during which the conditions appear stable can be somewhat non-representative for the long-term conditions of a site.

It is therefore advisable to benchmark the conditions encountered at the test sites with other longer-term records. In the simplest cases, this can be done by using longer term records of the same parameters measured at the same sites. For example, two of the TMT candidate sites, San Pedro Mártir and Mauna Kea have, over the years, seen many site characterization efforts [see for example, Refs. 13–15]. A similar case is encountered when a long-term data set exists for a site close to a test site, as is the case for Cerro Armazones, which is close to Cerro Paranal and the site of the VLT Astronomical Site Monitor. Of course, the issue of calibration and comparability of non-identical equipment arises here, but it is not necessarily required to compare the data taken by other equipment with those of the site testing suite. One only needs to establish whether the conditions within the external data set are the same during the site testing period and the overall acquisition period.

Along the same lines, even some data that do not directly measure a parameter of interest might be used. As an example, long-term records of satellite remote sensing and meteorological climate data are available. While these do not provide direct measurements of the parameters relevant for the TMT candidate sites, they can be searched for changes in key climate characteristics that might affect the conditions at the sites and indicate non-representative periods.

3.2. Climate Change

A specific case, and even more difficult to address, is the potential shift of long-term and large-scale climate patterns. It is now accepted that the average temperature of the planet has been increasing rapidly for the last decades and will continue to do so.[16] The rising temperatures themselves might make a difference to observatory sites through an increase in infrared backgrounds and water vapor in the atmospheric column, which have an effect on the ability to do ground based astronomy at infrared wavelengths.[17,18]

In addition, it is not clear what other changes in climate or weather patterns go along with this. For example, the position of close bad weather patterns, such as the South American summer monsoon,[19] could shift and either deteriorate or improve the average amount of clouds and precipitation experienced by a site. As another example, changes in wind direction patterns might affect the local seeing, in particular of the lowest layers, if the surrounding terrain has varying characteristics in different directions, as has been show in the case of Cerro Paranal.[20]

To our knowledge, climate modeling has not yet advanced to the point where such changes can be modeled and predicted with sufficient accuracy for astronomical site testing. Thus, this is one of the big unknowns for the siting of an observatory with an expected life time of many decades. The only possible cause of action is to look for sites which are stable with respect to such potential climate changes, that is, sites that are far away from known bad weather patterns, do not have potentially turbulence creating terrain close-by in any directions even if, today, the wind never comes from those directions, etc. For practical reasons, this is obviously not always possible.

3.3. Extreme Parameter Values

A specific case of the issues raised in Sections 3.1 and 3.2 is when extreme values of parameters are required, for example for design specifications. The extreme values encountered during the site testing period will almost certainly be exceeded during the observatory lifetime. If no other data are available, this can only be addressed by statistical means, and a safety margin should be added in order to account for climate change. Of course, some of the design parameters, such as the maximum wind speed the observatory can sustain, might be determined not based on the site testing measurements, but from building codes (which, hopefully, are based on similar considerations).

3.4. Short Time Scale Considerations

Like parameter variations on long time scales, some short time scale variations of importance might also not be accessible with the available equipment due to its integration times and duty cycles. In many cases the statistical behavior of the parameter of interest is known and can be extrapolated from the existing measurements, but for some parameters the temporal power spectra are not known down to sufficiently short time scales. An example of this are the fast variations of the mesospheric sodium layer (see Section 5.2 for more details) about which, until recently, very little was known and which can introduce uncertainties in performance estimates of laser guide star AO systems. For the most part, the only way around this problem is the commissioning of additional equipment or experiments, as was done in the case of the sodium layer variations.[21]

4. TURBULENCE CHARACTERISTICS

As was shown in Section 2, the TMT site testing program put a strong emphasis on the measurement of atmospheric turbulence parameters. At the same time, it was understood that the site testing work could not be an engineering project if multi-year data sets were to be acquired that are comparable not just from year to year but also from site to site. Thus, we decided to use existing instruments that had previously been shown to provide accurate results and that can operate reliably and autonomously at sites with little infrastructure, meaning in particular the combined MASS/DIMM instrument. SODARs were added as one of the few instruments that, at the time, were able to sample the ground layer with high resolution, although it was not clear how accurate a calibration was possible. From an operational point of view they were, however, plug and play instruments. Many of the turbulence parameters of interest for TMT can be measured with these instruments, but, as always, additional information would be useful as well, if it were available. In this section, we summarize the kind of additional turbulence measurements that would be of direct use for the TMT Project.

4.1. Higher Resolution Profiles

The first-light AO system of TMT, NFIRAOS, is a multi-conjugate AO system with deformable mirrors (DM) at positions conjugate to 0 km (DM1) and 11.2 km (DM2) elevation above the ground. Its performance, and in particular its performance as a function of the position in the field of view, is therefore critically dependent on the distribution of turbulence around the conjugate altitude of DM2, a regime where the MASS provides very low resolution profiles, with the two highest layers being integrals over large elevation ranges and having assigned altitudes of 8 and 16 km. This results in a large uncertainty of the location and distribution of the turbulence around the DM2 altitude.

As an example, if a MASS measurement produces a profile with layers of identical strengths in the 8 and 16 km layers, these could be caused by there being in fact two layers at exactly these altitudes, or by one layer of twice the strength approximately half way in between, i.e., very close to the DM2 conjugate altitude, or by an infinite number of other combinations of distinct layers or continuous turbulence distributions. The generalized isoplanatic angle for two-DM systems, θ_2, goes to infinity if all turbulence is located at the conjugate altitudes of the two DMs and is the smaller the farther away the turbulence is located from them.[22] Thus, a performance estimate for NFIRAOS calculated from MASS profiles might have a reasonably large uncertainty, depending on the distribution of turbulence in the 8 and 16 km profile bins and their relative strengths compared to the rest of the turbulence. (This effect is, of course, only one of the error terms in the AO performance analysis and the uncertainty of the overall performance is smaller than that of only this term.)

There are a number of instruments which provide much higher resolution profiles than the MASS instrument, such as SciDAR or balloon-mounted turbulence sensors.[23, 24] These were infeasible for TMT site testing purposes for various reasons, but can, in principle, be employed if sufficient resources are available.

More recently a new analysis method has been developed for the MASS. This method relies on the non-negative least square method as well as improved boundary conditions to double the number of turbulence layers. In combination with the DIMM, the instrument can now measure a 13 layer turbulence profile.[25] This increased resolution, combined with the ability to select the height of each layer, within some limits, leads to a more accurate identification of the altitude of the strong turbulence layers and a more useful result for some AO applications.

The turbulence profiles in the first 800 m above the ground were measured with high spatial resolution using SODARs during the TMT site testing work. High spatial resolution of the ground layer is important for determining the effect that the height of the telescope and the enclosure will have on the seeing experienced by the observatory. It can also be potentially useful for determining the effect of leveling and preparation of the site on the seeing. A potential short-coming, depending on the application, of these measurements is their temporal resolution, as our SODAR measurements had to be averaged over 30 minutes in order to provide sufficient signal-to-noise ratio. Lunar scintillometers[26, 27] and SloDAR[28] are now established techniques which can measure the ground layer with higher temporal resolution than a SODAR and require only small apertures. Of course, one could also mount in-situ turbulence monitors, such as micro-thermal probes or sonic anemometers, on sufficiently high masts, tethered balloons or kites.

A different kind of turbulence resolution is the issue of distribution of turbulence strength as a function of direction of observation. It has been shown previously that such dependences can exist[29] and some preliminary investigation for Mauna Kea 13N using TMT data were done. It turns out that the TMT data do not cover a sufficiently large range of zenith and azimuth angles for this purpose and that, ideally, simultaneous measurements with several instruments pointing in different directions should be used.[30, 31] This is not a fundamental problem, as it can be addressed by frequently changing the star list of the DIMM and MASS instruments and/or operating several such instruments simultaneously.

4.2. Turbulence Coherence Time and High Elevation Winds

Measuring the coherence time, τ_0, accurately is limited by our ability to measure both the turbulence and wind profiles accurately:

$$\tau_0 = 1.5654 \times 10^{-6} \left(\int C_n^2(h) V(h)^{5/3} dh \right)^{-3/5} \tag{1}$$

For this reason, instruments that have access to both are currently used for this purpose, such as SciDAR and balloon-mounted microthermal probes. These instruments, however, as pointed out earlier, were not well suited for the long term and robotic nature of the TMT site testing campaign. With some ingenuity, and relying on the similitude between the equation above and the equation for the MASS differential scintillation index,[32] an approximate value of τ_0 can be obtained from the MASS scintillation measurements. Further measurements and simulations have however shown that this relationship is difficult to calibrate and moreover is a function of the location and strength of the turbulence.[33, 34] The development of a new dedicated instrument such as FADE[35] should provide a good solution for future campaigns of similar nature.

4.3. Outer Scale of Turbulence

The outer scale of turbulence, L_0, is a parameter not measured with the TMT site testing equipment. The seeing calculated with these instruments is therefore defined for Kolmogorov turbulence only or, in other words, for an infinite outer scale, and must not be confused with the image quality a large-aperture telescope would experience under those conditions.

Besides its impact on the full-width at half maximum (FWHM) of a large-aperture telescope, a finite value of L_0 also has a direct effect on the turbulent power distribution into modes of different spatial scale. In particular, a small outer scale reduces the power in the lower order modes with respect to turbulence with a larger outer scale and the same measured DIMM seeing. This has a direct effect on both AO system performance and some aspects of its design, such as the stroke requirements of the deformable mirrors and tip-tilt stages.

Measuring the outer scale at the candidate sites was not feasible in the framework of the TMT site testing program. While compact outer scale monitors existed even before the beginning of the program, such as the Generalized Seeing Monitor (GSM),[36] they are generally only semi-automatic and adapting them to work as autonomous robotic systems at remote sites, while generally possible, was beyond the available resources. Instead, a median value of 30 m is generally assumed for L_0 for TMT performance estimates, as this value has been found to be close to the median value measured at most sites tested to date with the GSM (see Ref. 36 as well as the later publications of the GSM team). It is, however, understood that large variations of L_0 occur even over short time scales and that very large values occur frequently at all sites. This is taken into account in the TMT AO design process.

Other methods of measuring the outer scale of turbulence usually rely on large aperture telescopes or interferometric means (see, for example, Ref. 37) which can be employed at sites with existing observatories, but are impractical for undeveloped sites. Work is also being done on outer scale profilers.[38]

5. OTHER PARAMETERS AND CONSIDERATIONS

5.1. Clouds, Atmospheric Transparency and Sky Brightness

Assessing cloud cover in a qualitative or semi-quantitative way is a simple task for the human observer. Performing an automated quantitative analysis is much more difficult. Cloud cover estimates of the TMT candidate sites were obtained from ASCA and MASS flux measurements and were used to supplement data from several studies of satellite data. Details are given in TST-9 and only a brief summary is presented here.

The ASCAs at the TMT candidate sites took images using several optical and near-infrared filters every few minutes during night time. A photometric analysis of these images was attempted but suffered from several practical problems, such as the large pixel size on the sky and the non-constant background levels. Thus, the final assessment of cloud cover using on-site data, was done by visual inspection of movies of ASCA images, taking advantage of the aforementioned pattern recognition skills of the human eye and brain. A comparison with the cloud cover analysis done using satellite data produced results consistent within the expected uncertainties of each method.

A quantitative analysis of atmospheric transparency, cirrus clouds, high elevation dust and sky brightness from ASCA images was not possible in the available time due to the issues with the photometric analysis mentioned above. The same holds true for the use of the stellar fluxes measured by the MASS instruments. Our investigations (see TST-9) led us to believe that a careful treatment of the available data could yield measurements of atmospheric transparency with uncertainties of $\sim$0.1 to 0.2 magnitudes, but this work was not finished due to the time constraints of the project. In either case, the images from an instrument more suitable to the specific task would be preferable. One example, for Mauna Kea, is the analysis of Skyprobe data at the Canada-France-Hawaii Telescope (CFHT).[39] Other dedicated cloud detection equipment exists, see Refs. 40 and 41 for examples of a custom-built and a commercial instrument.

5.2. Sodium Layer Properties

The density, altitude and thickness of the mesospheric sodium layer and their variations have a direct effect on the performance and design of laser guide star AO systems like NFIRAOS. Sodium layer properties were not measured at the TMT candidate sites as this would have been beyond the available resources of the project. This was deemed an acceptable risk, as the average mesopheric sodium levels are generally considered to be mostly a function of latitude and time of the year and some data exist for some of the TMT candidate sites or close-by locations.

A larger potential problem was the lack of knowledge about the behavior of the sodium on time scales faster than tens of seconds to minutes. Measurements of this behavior were not feasible during TMT site testing as a large-aperture telescope is required. Much progress in our understanding of the sodium layer has since been gained using a LIDAR system at the Large Zenith Telescope (LZT) and is presented in another paper at this conference.[21]

5.3. Precipitable Water Vapor

The integrated precipitable water vapor (PWV) in the atmospheric column and its distribution is of relevance for the characterization of the thermal background level and absorption in the infrared bands. TMT site testing included the use of infrared radiometers, IRMA, for PWV monitoring. The IRMA units were deployed relatively late in the site testing effort on only three sites (see Table 2) and therefore did not provide sufficient data for a full characterization of the sites. For a more comprehensive characterization the strategy was then to use surface measurements of temperature and humidity, together with median values of the water vapor scale height from the analysis of radiosonde soundings. Additionally, 215 GHz and 225 GHz radiometer data together with the use of models to transfer optical depths into PWV were used at San Pedro Mártir and Mauna Kea.[18]

The strategy of using surface data and radiometry data from datasets provided a good characterization of the PWV at the sites on seasonal and global scales. It was, however, not successful to characterize short term fluctuations. More importantly, it cannot be used to provide an accurate picture of the variations of the water vapor scale height, which is important for looking in detail at the absorption line broadening and thermal background.

5.4. Presentation of the Data

The presentation of the vast amount of data accumulated during TMT site testing is an applied rather than a fundamental issue, and applies to virtually all data sets available for astronomical observatory sites. As stated and illustrated with examples in TST-1, there is no single way of representing site testing results that is applicable to all applications.

A particular case of importance to adaptive optics is the calculation of representative turbulence profiles. Ideally, performance estimates of an instrument, AO system or observatory should be done using each individual profile measured for the site, and statistics of the relevant metric should be assembled afterwards. In practice, this is not always possible due to the computational effort involved and one needs to work with a smaller set of representative profiles. The problem then is that a profile that is representative in one aspect, for example in a median value sense of an integrated parameter, might not be representative of median conditions of other aspects. We have previously described this problem in Ref. 42.

While one of the products of TMT site testing is of course a vast set of graphical and tabular representations of the site testing results as summarized in the TST series, no such set can provide all the information needed for all potential uses. The TMT site testing data have therefore been made public in an on-line database[3] such that all interested parties are able to produce the kind of results relevant to their respective applications.

6. SUMMARY

Site testing projects have been addressing the same basic questions about the quality of observatory sites for more than a century, with the details of methods and parameters of interest becoming increasingly more complex. Nevertheless, any site characterization effort always leaves open questions that cannot be answered with the available data. We have used the example of the TMT site testing project to illustrate some of the currently open questions, to explain why they were not addressed as part of the TMT site testing work, and what can be done to measure the respective characteristics if they become sufficiently important for a project, including TMT itself, that such an effort is warranted.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.

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